

Influence of aerobic fitness and body fatness on tolerance to uncompensable heat stress

GLEN A. SELKIRK,¹ AND TOM M. McLELLAN^{1,2}

¹Faculty of Physical Education and Health, Exercise Science, University of Toronto, Toronto M5S 2W6; and ²Environmental and Applied Ergonomics Section, Defence and Civil Institute of Environmental Medicine, Toronto, Ontario, Canada M3M 3B9

Received 27 March 2001; accepted in final form 18 July 2001

Selkirk, Glen A., and Tom M. McLellan. Influence of aerobic fitness and body fatness on tolerance to uncompensable heat stress. *J Appl Physiol* 91: 2055–2063, 2001.—This study examined the independent and combined importance of aerobic fitness and body fatness on physiological tolerance and exercise time during weight-bearing exercise while wearing a semipermeable protective ensemble. Twenty-four men and women were matched for aerobic fitness and body fatness in one of four groups (4 men and 2 women in each group). Aerobic fitness was expressed per kilogram of lean body mass (LBM) to eliminate the influence of body fatness on the expression of fitness. Subjects were defined as trained (T; regularly active with a peak aerobic power of 65 ml·kg LBM⁻¹·min⁻¹) or untrained (UT; sedentary with a peak aerobic power of 53 ml·kg LBM⁻¹·min⁻¹) with high (High; 20%) or low (Low; 11%) body fatness. Subjects exercised until exhaustion or until rectal temperature reached 39.5°C or heart rate reached 95% of maximum. Exercise times were significantly greater in T_{Low} (116 ± 6.5 min) compared with their matched sedentary (UT_{Low}; 70 ± 3.6 min) or fatness (T_{High}; 82 ± 3.9 min) counterparts, indicating an advantage for both a high aerobic fitness and low body fatness. However, similar effects were not evident between T_{High} and UT_{High} (74 ± 4.1 min) or between the UT groups (UT_{Low} and UT_{High}). The major advantage attributed to a higher aerobic fitness was the ability to tolerate a higher core temperature at exhaustion (the difference being as great as 0.9°C), whereas both body fatness and rate of heat storage affected the exercise time as independent factors.

rectal temperature; protective clothing; heat tolerance; heat storage; metabolic rate

MANY OCCUPATIONAL SETTINGS necessitate the use of protective clothing and equipment to combat hazardous environments. Typically, these protective ensembles restrict avenues for body heat loss, creating a condition where the required evaporative cooling (E_{req}) necessary for the body to achieve a thermal steady state exceeds the maximum evaporative potential of the environment. Such a situation defines a condition of uncompensable heat stress (30), where the body continues to store heat and core temperature continues to rise to dangerously high levels. The heat strain asso-

ciated with wearing the military's current-issue biological and chemical protective clothing has been well documented for a variety of environmental conditions (1, 8, 17, 26, 32, 35, 36, 39).

During uncompensable heat stress, exercise time can be influenced by the initial and final core or rectal temperature (T_{re}), the heat capacity of the body ($C_{p,b}$), and the rate of heat storage ($\dot{S}$) as shown in the following equation (12)

$$\text{Exercise time} = (T_{re,final} - T_{re,initial}) \cdot C_{p,b} \cdot (\dot{S} \cdot 60)^{-1} \quad (1)$$

where $T_{re,final}$ and $T_{re,initial}$ are final and initial T_{re} , exercise time is expressed in minutes, T_{re} is in °C, $C_{p,b}$ is in J·kg⁻¹·°C⁻¹, and $\dot{S}$ is in W/kg. To better understand the ways to affect exercise time, modifiers of the principal components within this equation need to be examined. For example, factors such as high aerobic fitness (2, 9), heat acclimation (2, 3), and the follicular phase of the menstrual cycle (46) have all been shown to lower the initial core temperature and prolong exercise time. Conversely, factors that raise the starting T_{re} , such as hypohydration (9, 10) or the luteal phase of the menstrual cycle (46), are associated with shorter exercise times. It has also been shown that the T_{re} tolerated at exhaustion and exercise times are influenced by aerobic fitness (9) and body fatness (33). Cross-sectional comparisons have revealed that individuals with a high aerobic fitness have longer exercise times than their less fit counterparts because of a lower starting T_{re} and a higher T_{re} tolerated at exhaustion (9). Recent evidence has documented that fatigue during heat stress is associated with the attainment of a critically high core temperature approaching 40°C for endurance-trained subjects (19, 20, 40, 41). Yet these findings cannot be generalized to all individuals because others have reported that exhaustion from heat strain occurs at a lower mean core temperature, between 38.5 and 39°C for subjects with varied fitness levels (31, 39, 43). Sawka et al. (43), however, found no relationship between the range in maximal aerobic power ($\dot{V}O_{2,max}$) of 45–65 ml·kg⁻¹·min⁻¹ and the core temperature that could be tolerated at exhaustion for

Address for reprint requests and other correspondence: T. M. McLellan, Defence and Civil Institute of Environmental Medicine, Head/Environmental and Applied Ergonomics Section, P.O. Box 2000, Toronto, ON, Canada M3M 3B9 (E-mail: tom.mclellan@dciem.dnd.ca).

The costs of publication of this article were defrayed in part by the payment of page charges. The article must therefore be hereby marked "advertisement" in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

17 heat-acclimated subjects during uncompensable euhydrated and hypohydrated heat-stress trials.

The classic description of the cardiovascular response to heat stress involves a progressive increase in the redistribution of the central blood volume to the cutaneous circulation to increase convective and evaporative heat loss, resulting in a lowered venous return, stroke volume, central venous pressure, and mean arterial pressure (42). If the rise in body temperature is sufficiently high, the pooling of blood in the cutaneous circulation may lead to circulatory collapse and a state of unconsciousness. It is tempting to suggest that the untrained, compared with the endurance trained, may experience greater circulatory strain at any given core temperature during heat stress because of their lower blood volume and stroke volume (27) and that these differences may account for the lower core temperature tolerated at exhaustion.

In addition to those factors that influence the $T_{re,initial}$ and $T_{re,final}$, exercise time is also influenced by the tissue $C_{p,b}$. Adipose tissue has a lower heat capacity compared with lean tissue, such as blood, muscle, water, and bone (15). Therefore, individuals with a higher percentage of body fat will have a lower whole $C_{p,b}$ (28) and, therefore, a faster rate of increase in core temperature for a given S . If a value of 4 vs. 2 $\text{kJ}\cdot\text{kg}^{-1}\cdot\text{C}^{-1}$ is used for the heat capacity of lean vs. adipose tissue (15), then individuals that differ in body fatness by 15% would differ in their $C_{p,b}$ by ~8%. Women typically have a significantly higher body fat content compared with men, and it is not surprising that they are at a thermoregulatory disadvantage during uncompensable heat stress (33). However, differences in exercise time between men and women during uncompensable heat stress approach 25% and thus exceed the differences that might be attributed to differences in body fatness alone (33). In addition to differences in body fatness, women also have a lower aerobic fitness and tolerate a lower core temperature at exhaustion compared with men (33). The conclusion regarding the benefits of aerobic fitness reported by Cheung and McLellan (9) also was confounded by the fact that their high-fit subjects had a significantly lower body fatness of 11.5% compared with the 21% levels for their less fit subjects. It is not entirely clear, therefore, whether aerobic fitness, or body fatness, or both contributed to the differences in exercise time between the fitness groups compared by Cheung and McLellan.

Therefore, the purpose of this study was to determine the separate and combined importance of aerobic fitness and body fatness on exercise time during uncompensable heat stress. This was achieved by matching subjects within four groups defined by high and low levels of both fitness and fatness. It was hypothesized that, when a protective clothing ensemble is worn, individuals with a high aerobic fitness through regular training would exhibit enhanced exercise times. In addition, it was hypothesized that individuals with low body fatness would also exhibit increased exercise times because of their increased capacity to store heat per unit of mass.

METHODS

Subjects. Twenty-four subjects (16 men and 8 women) were selected from a subject pool of 49 healthy volunteers who had all completed the heat-stress trials described below. Recent studies have shown that between 12 and 15 subjects are necessary to obtain a power of 0.8 for the dependent measure of exercise time (9, 46). Thus, in the present experimental design, the main effects of fitness and fatness were evaluated with 12 subjects in each level of the different factors. Testing was performed in the climatic chamber at the Defence and Civil Institute of Environmental Medicine (DCIEM) following approval by both DCIEM and the University of Toronto ethics committees. Preceding participation, the subjects were medically screened with a 12-lead electrocardiogram, and physical exam and a full explanation of procedures, discomforts, and risks were given before written informed consent was obtained.

Definition of groups. Subjects were matched for aerobic fitness and body fatness in a 2×2 factorial design. Aerobic fitness was expressed relative to lean body mass (LBM) to eliminate the influence of body fatness on the expression of fitness. The four groups were defined as endurance trained (T) or untrained (UT) with low (Low) or high levels of body fatness (High). The T subjects were those individuals engaged in regular aerobic exercise (4–5 times/wk) and had a measured peak aerobic power ($\dot{V}O_{2\text{peak}}$) greater than ~65 and 60 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ for men and women, respectively. The UT subjects were not involved in a regular aerobic exercise program and had a $\dot{V}O_{2\text{peak}}$ <55 and 50 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ for men and women, respectively. Grouping factor averages are shown in Table 1.

To allow a separation between groups, high body fatness was defined as $\geq 18\%$ of total body mass, whereas low body fatness was defined as $\leq 13\%$ of total mass. The groups T_{Low} and UT_{Low} and the groups T_{High} and UT_{High} were matched for fatness but differed in fitness. Similarly, the groups T_{Low} and T_{High} and the groups UT_{High} and UT_{Low} were matched for fitness but differed in fatness. Each group consisted of six matched subjects: four men and two women.

Determination of $\dot{V}O_{2\text{peak}}$. $\dot{V}O_{2\text{peak}}$ was measured by using open-circuit spirometry (36) on a motorized treadmill. Heart rate (HR) was monitored during the treadmill protocol by using a transmitter/telemetry unit (Polar Vantage XL). The highest value recorded at the end of the exercise test was defined as peak HR (HR_{peak}). Subjects' physical activity profile was obtained from a verbal questionnaire to determine the presence or absence of regular involvement in aerobic activities.

Body surface area was calculated using the Dubois equation (A_D) (13). Body density was determined from underwater

Table 1. $\dot{V}O_{2\text{peak}}$ expressed relative to LBM and body fatness levels used to classify groups as T and UT with low or high levels of body fatness

Group	$\dot{V}O_{2\text{peak}}$, $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$	Body Fatness, %
T_{Low}	64.7 $\pm$ 2.0 (56.7–69.5)§	10.9 $\pm$ 0.8 (8.2–12.8)
T_{High}	64.6 $\pm$ 2.4 (58.6–72.3)‡	18.8 $\pm$ 1.0 (17.6–21.9)*
UT_{Low}	53.3 $\pm$ 2.0 (47.0–59.5)	12.4 $\pm$ 1.0 (9.2–14.1)
UT_{High}	52.3 $\pm$ 1.2 (50.6–58.0)	21.2 $\pm$ 1.0 (17.5–24.6)†

Values are means $\pm$ SE (ranges in parentheses). $\dot{V}O_{2\text{peak}}$, peak aerobic power; LBM, lean body mass; T, trained; UT, untrained; Low, low levels of body fatness; High, high levels of body fatness. Significant differences: * T_{High} vs. T_{Low} ; † UT_{High} vs. UT_{Low} ; ‡ T_{High} vs. UT_{High} ; § T_{Low} vs. UT_{Low} , $P < 0.05$.

weighing by using helium dilution to determine residual lung volume. Body fatness was calculated from the measured body density by using the Siri equation (44). LBM was calculated by subtracting the calculated mass of body fat from the total body mass.

Experimental design. All subjects performed a familiarization exposure to the hot-dry environmental conditions (40°C, 30% relative humidity, wind speed <0.1 m/s) 1 wk before the experimental trial to limit the acute effects of acclimation. The familiarization session included wearing a protective clothing ensemble with respirator and cannister. The heat-stress trials were performed while wearing this same military biological and chemical protective ensemble and walking on a level treadmill at 0.97 m/s (3.5 km/h). Subjects were asked to refrain from hard exercise (i.e., running, swimming, cycling, and weight lifting), alcohol, nonsteroidal anti-inflammatories, and sleep medication 24 h before each session and also to refrain from ingesting caffeine or nicotine 12 h before each session. Although nonsmokers would have been preferred, it was difficult to find and match subjects in terms of fitness and fatness. Three subjects in UT_{Low}, one in UT_{High}, and one in T_{High} smoked cigarettes. Women matched for either fitness or fatness were tested during the follicular phase to control for the influence of menstrual phase on temperature regulation during uncompensable heat stress (46). End-point criteria for each heat-stress trial included 4 h of continuous exercise; T_{re} reaching 39.5°C; HR reaching or exceeding 95% of maximum for 3 min; dizziness or nausea precluding further exercise; subject exhaustion or discomfort due to the encapsulation of the clothing ensemble and respirator; or the investigator terminating the trial. Exercise time was defined for all trials as the elapsed time from the beginning of the exercise to the attainment of one or more of the end-point criteria that resulted in removal from the chamber.

Clothing ensembles. Normal military operational clothing configuration was worn beneath the protective ensemble, consisting of underwear, shorts, T-shirt, combat clothing, and running shoes. The protective clothing ensemble consisted of a semipermeable overgarment and impermeable rubber gloves and overboots, and a respirator and cannister. The total thermal resistance of the biological and chemical protective ensemble, determined with a heated copper manikin at a wind speed of 1.11 m/s, was 0.291 m²·°C·W⁻¹ (1.88 clo) (18). The Woodcock vapor permeability coefficient, determined with a completely wetted manikin, was 0.33 (18).

Dressing and weighing procedures. To control for the effects of circadian rhythm on core temperature, all trials began at ~8:00 AM (34). Subject preparation and dressing procedures were described in detail previously (34). Each subject ingested 200 ml of warm water at ~37°C to reduce any heat-sink effect, before entering the chamber and every 15 min during the exercise. If T_{re} was >39°C or if the subject felt that he or she could not continue for another 10 min, water was not administered for the remainder of the test.

Physiological measurements. Mean values over 1-min periods for T_{re} and a 12-point weighted mean skin temperature (T_{sk}) were calculated, recorded, and printed by the computerized data-acquisition system. T_{re} was measured using a flexible vinyl-covered rectal thermistor (Pharmaseal APC 400 series) inserted ~15 cm beyond the anal sphincter. T_{sk} was calculated from 12 heat-flow transducers (Concept Engineering, FR-025-TH4403S-F8-F) using a weighted equation (47). HR was monitored using a transmitter (Polar Vantage XL) clipped to electrocardiogram leads or an elasticized belt that was fitted around the chest and taped in place. The receiver was taped to the outside of the clothing, allowing for a continuous HR display. HR was recorded manually

every 5 min during the heat-stress test. Open-circuit spirometry was used to determine expired minute ventilation, aerobic power ($\dot{V}O_2$), and carbon dioxide production every 15 min from values averaged over a 2-min sampling period. An adapter was placed on the exhaust valve of the respirator to allow gas-exchange collection.

Sweat measurements. Differences between nude and dressed body masses before and after each trial were corrected for respiratory (38) and metabolic weight losses (45) as well as for fluid intake. The rate of sweat produced (SR) was calculated as the sum of pretrial nude body mass and fluid given minus posttrial (corrected) nude body mass divided by exercise time.

Blood sampling and measurements. Before the heat-stress trial was begun, a 5-ml venous blood sample was obtained from all subjects to determine osmolality using plasma concentrations of glucose, sodium, and blood urea nitrogen (Nova Ultra Stat, Nova Biomedical). An additional 5-ml sample was collected from the women for verification of menstrual cycle phase. Radioimmunoassays, in duplicate, were used to determine estradiol and progesterone (DSL-4800 Ultra-Sensitive Estradiol Radioimmunoassay Kit, and KSL-3900 ACTIVE Progesterone Coated-Tube Radioimmunoassay Kit, respectively, Diagnostics Systems Laboratories).

Subjective measurements. Two subjective ratings of overall perceived exertion (RPE) (5) and a rating of thermal comfort (RTC) (14) were completed every 15 min after metabolic gas-exchange measurements. Both scales were each presented on large charts, and subjects were asked to indicate their current rating using their index finger. The scale for RPE ranged from 0 (nothing) to 10 (maximum), and RTC was a modified version of a scale ranging from 7 (comfortable) to 13 (intolerably hot).

Calculation of heat exchange and heat storage. The $\dot{S}$ (in W/kg) was calculated from the heat balance equation as

$$\dot{S} = \dot{M} - \dot{W} + (\dot{C} + \dot{R}) + \dot{K} + \dot{C}_{resp} - \dot{E}_{resp} - \dot{E}_{sk} \quad (2)$$

where $\dot{M}$ is metabolic heat production, $\dot{W}$ is rate of external work, $\dot{C}$ is convective heat gain, $\dot{R}$ is radiative heat gain, $\dot{K}$ is conductive heat gain, $\dot{C}_{resp}$ is respiratory convective heat gain, $\dot{E}_{resp}$ is respiratory heat loss, and $\dot{E}_{sk}$ is skin evaporation rate. Details about the specific equations used to determine the components of the heat balance equation when protective clothing is worn have been presented elsewhere (33, 34). The E_{req} was determined from the heat balance equation without including the impact of evaporative heat loss from the skin. The maximum evaporative capacity of the environment (E_{max}) was calculated from the following equation by Gonzalez et al. (18)

$$E_{max} = 16.5 \cdot (0.33/0.291) \cdot (P_{sk} - P_a) \quad (3)$$

where 16.5 is the Lewis relation (°C/kPa), 0.33 is the Woodcock vapor permeability coefficient, 0.291 is the total insulation of the clothing ensemble, P_{sk} is the skin vapor pressure assuming 100% saturation at T_{sk} , and P_a is the ambient water vapor pressure (2.2 kPa for 40°C and 30% relative humidity).

Total heat storage (S , in kJ/kg) was calculated from $\dot{S}$ values averaged every 5 min and exercise time (34) as

$$S = \frac{\dot{S} \cdot (60 \cdot \text{time})}{1,000} \quad (4)$$

Statistical analyses. A three-factor ANOVA with two grouping factors (fitness and fatness) and one repeated factor (time) was performed on the dependent measures sampled over time, (i.e., T_{re} , T_{sk} , $\dot{S}$, $\dot{M}$, and HR). The T and UT groups

Table 2. Physical characteristics of age, height, mass, LBM, A_D , A_D /mass, HR_{peak} and $\dot{V}O_{2peak}$ for T and UT groups with high or low body fatness

Group	Age, yr	Height, cm	Mass, kg	LBM, kg	A_D , m ²	A_D /mass, m ² ·kg ⁻¹ ·10 ⁻³	HR_{peak} , beats/min	$\dot{V}O_{2peak}$, ml·kg ⁻¹ ·min ⁻¹
T _{Low}	25.2 ± 2.5	168.5 ± 4.6	61.30 ± 4.38	54.70 ± 4.22	1.69 ± 0.09	2.79 ± 0.08	195.2 ± 4.4	57.91 ± 2.04§
T _{High}	22.5 ± 0.9	174.1 ± 5.1	73.80 ± 6.66	60.00 ± 5.37	1.88 ± 0.11	2.58 ± 0.09	194.2 ± 3.1	52.92 ± 1.87*†
UT _{Low}	22.2 ± 0.8	171.6 ± 5.1	62.00 ± 3.25	54.30 ± 2.84	1.72 ± 0.07	2.78 ± 0.07	196.0 ± 1.7	46.43 ± 2.10
UT _{High}	21.2 ± 0.5	175.0 ± 3.9	78.70 ± 6.89†	62.20 ± 6.10	1.93 ± 0.10	2.50 ± 0.10†	198.8 ± 3.2	41.87 ± 1.03†

Values are means ± SE. A_D , Dubois body surface area; A_D /mass, ratio of A_D to mass; HR_{peak} , peak heart rate. Significant differences: *T_{High} vs. T_{Low}; †UT_{High} vs. UT_{Low}; ‡T_{High} vs. UT_{High}; §T_{Low} vs. UT_{Low}, $P < 0.05$.

were analyzed up to and including 75 and 60 min, respectively, maintaining an n of 6 for all data points. In addition, a two-factor ANOVA with two grouping factors (fitness and fatness) was calculated for the dependent measures recorded at discrete time intervals (i.e., exercise time, SR, and S). Planned post hoc comparisons were made between the groups using a Newman-Keuls adjustment for multiple comparisons. Post hoc analyses were performed only between groups matched for fitness or fatness. Thus T_{Low} was never compared with UT_{High}, and similarly T_{High} was not compared with UT_{Low}. All ANOVAs were performed using statistical software (SuperAnova version 1.11, 1991, Abacus Concepts). For all statistical analyses, an α -level of 0.05 was used. Data are presented as means ± SE.

RESULTS

Subjects. The high-fat groups had a significantly greater combined body mass and A_D , plus a lower A_D -to-mass ratio, compared with the low-fat groups. Furthermore, UT_{Low} had a significantly greater A_D -to-mass ratio compared with UT_{High}. $\dot{V}O_{2peak}$ expressed per unit of total mass (ml·kg⁻¹·min⁻¹) was significantly greater for T compared with UT and for low-compared with high-fatness groups. There were no other statistically significant anthropometric differences among the groups (Table 2).

Blood. The mean values for estradiol (92.5 pmol/l) and progesterone (5.1 nmol/l) were within normal

ranges for the early follicular phase. There were no significant differences in osmolality among the groups, with mean values approximating 285 mosmol/kgH₂O, indicating similar hydration levels before the heat exposure.

Heat-stress trial. The ratio of E_{req} to E_{max} varied nonsignificantly from 2.2 to 2.4 among the four groups, indicating that the severity of the uncompensable heat stress was similar.

Exercise time. Exercise time and reasons for termination of the heat-stress trial are described in Table 3. There was an interaction of both fitness and fatness on exercise time. Post hoc analyses revealed that the power of this interaction effect was 0.82. T_{Low} had a significantly greater exercise time compared with T_{High} and UT_{Low}, whereas no difference was observed between the groups matched for a high body fatness or low aerobic fitness. None of the trials approached the 4-h time limit. All of the subjects in T_{Low} ended their trial, having reached the ethical ceiling for T_{re} of 39.5°C, whereas other reasons for termination were more evident with the other groups (Table 3). The relationship between $T_{re,final}$ and $\dot{V}O_{2peak}$ expressed relative to either total mass ($r = 0.51$) or LBM ($r = 0.44$) was not significant for the subjects who terminated their trial because of exhaustion or nausea.

T_{re} . The values for $T_{re,initial}$, $T_{re,final}$, and change in T_{re} (ΔT_{re}) are given in Table 4. There were no significant differences in $T_{re,initial}$. There was a significant effect of fitness level on $T_{re,final}$, with values 0.9°C greater for T_{Low} compared with UT_{Low} and 0.4°C greater for T_{High} compared with UT_{High}. Post hoc power analyses for $T_{re,final}$ revealed a value of 0.97 for the main effect of fitness. Both T groups had a greater

Table 3. Exercise time and reasons for test termination during the heat-stress trial conducted at 40°C and 30% relative humidity, with subjects wearing the protective clothing ensemble for T and UT groups with high or low body fatness

	T _{Low}	T _{High}	UT _{Low}	UT _{High}
Exercise time				
Min	116.2 ± 6.5†	82.2 ± 3.9*	69.5 ± 3.6	73.7 ± 4.1
Range	100–147	74–101	62–86	60–85
Reason for termination				
T_{re}	6	1		2
Exhaustion		3	2	3
Discomfort			2	1
HR			2	
Nausea		2		

Values for exercise time are means ± SE, with ranges also shown. Reasons for test termination are presented as no. of subjects for rectal temperature (T_{re} ; 39.5°C), exhaustion, discomfort, heart rate (HR; ≥95% HR_{peak} for 3 min), and nausea. *T_{High} significantly different from T_{Low}; †T_{Low} significantly different from UT_{Low}, $P < 0.05$.

Table 4. $T_{re,initial}$, $T_{re,final}$, and ΔT_{re} during the heat-stress trial conducted at 40°C and 30% relative humidity, with subjects wearing the protective clothing ensemble for T and UT groups with high or low body fatness

Group	$T_{re,initial}$, °C	$T_{re,final}$, °C	ΔT_{re} , °C
T _{Low}	37.02 ± 0.08	39.48 ± 0.01†	2.46 ± 0.08†
T _{High}	37.10 ± 0.09	39.22 ± 0.09‡	2.12 ± 0.12*†
UT _{Low}	37.19 ± 0.08	38.58 ± 0.19	1.39 ± 0.19
UT _{High}	37.26 ± 0.15	38.78 ± 0.24	1.52 ± 0.11

Values are means ± SE. $T_{re,initial}$, $T_{re,final}$, and ΔT_{re} : initial, final, and change in T_{re} , respectively. Significant differences: *T_{High} vs. T_{Low}; †T_{Low} vs. UT_{Low}; ‡T_{High} vs. UT_{High}, $P < 0.05$.

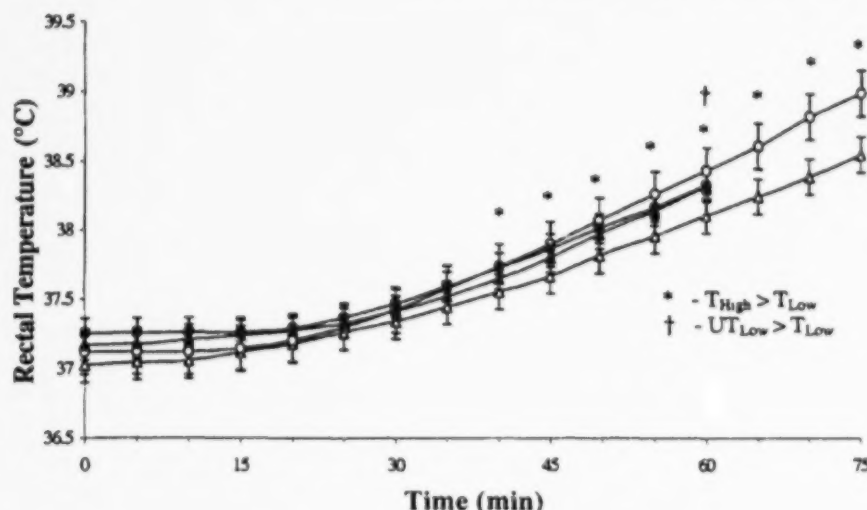


Fig. 1. Rectal temperature response during the heat-stress trial conducted at 40°C and 30% relative humidity, with subjects wearing a protective clothing ensemble for trained (T) or untrained (UT) groups with low (Low) or high body fatness (High). Values are means $\pm$ SE. Δ , T_{High} ; $\circ$, T_{Low} ; $\blacktriangle$, UT_{High} ; $\bullet$, UT_{Low} . Significant differences * T_{High} vs. T_{Low} ; $\dagger UT_{Low}$ vs. T_{Low} , $P < 0.05$.

ΔT_{re} compared with their corresponding UT groups. In addition, ΔT_{re} was significantly greater for T_{Low} compared with T_{High} .

The T_{re} response throughout the heat-stress trial is shown in Fig. 1. There were no significant differences in T_{re} over the first 30 min. At 40 min, T_{re} of T_{High} was significantly greater than that of T_{Low} , and these differences remained for the duration of the heat-stress trial. In addition, after 60 min of exercise, T_{re} was significantly higher for UT_{Low} compared with T_{Low} .

T_{sk} . T_{sk} response for T_{High} was significantly greater at 65 min compared with that for T_{Low} . There were no other differences in T_{sk} among the groups during the heat-stress exposure (Fig. 2). There were no significant differences in initial or final T_{sk} among the groups.

HR. After 20 min of heat-stress exposure, HR values were significantly higher for T_{High} (109.8 ± 4.8 beats/

min) compared with T_{Low} (100.2 ± 4.6 beats/min). These significant differences continued for the remainder of the exercise. Similarly, after 15 min of exercise, the HR for UT_{Low} (113.2 ± 7.0 beats/min) was significantly greater than for T_{Low} (99.5 ± 6.4 beats/min). After 1 h of exercise, these differences had increased to almost 30 beats/min, with values of 128.7 ± 5.8 and 156.7 ± 7.0 beats/min for T_{Low} and UT_{Low} , respectively. Only two subjects, both in UT_{Low} , reached the HR cutoff during the trials (see Table 3). Final HR showed no significant differences among the matched groups, with an overall average of 166 beats/min. Final HR, expressed as a percentage of HR_{peak} , did not exceed 90% (89 ± 3 , 82 ± 4 , 84 ± 2 , and $87 \pm 3\%$ HR_{peak} for UT_{Low} , UT_{High} , T_{Low} , and T_{High} , respectively).

Oxygen cost of exercise. When the expression of $\dot{V}O_2$ was normalized for differences in body mass, the re-

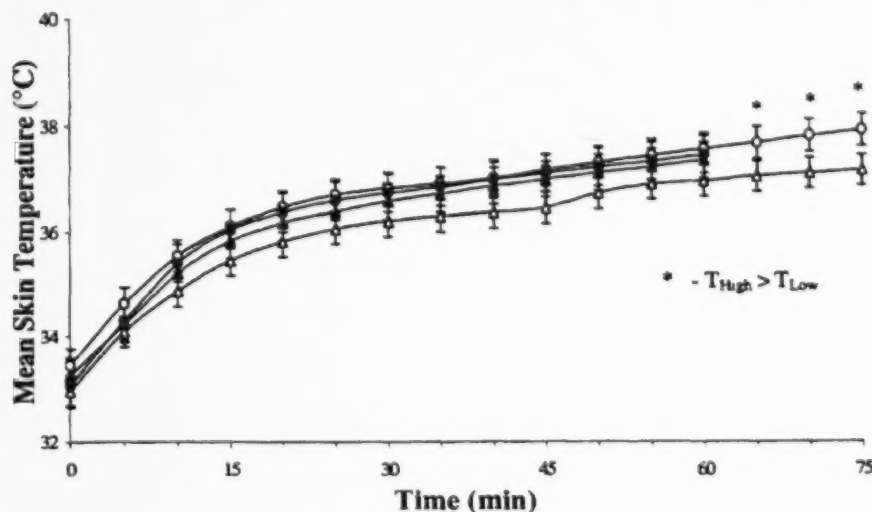


Fig. 2. Mean skin temperature response during the heat-stress trial conducted at 40°C and 30% relative humidity, with subjects wearing a protective clothing ensemble for T or UT groups with low or high body fatness. Symbols are as defined in Fig. 1. Values are means $\pm$ SE. *Significant difference, T_{High} vs. T_{Low} , $P < 0.05$.

sponse for UT_{High} over 60 min of exercise was significantly reduced ($11.3 \pm 0.4 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$) compared with the other matched groups (12.4 ± 0.4 and $12.5 \pm 0.6 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ for T_{High} and UT_{Low} , respectively). Corresponding values for T_{Low} were $11.9 \pm 0.4 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$. Differences between T_{Low} and T_{High} became significant after 60 min of heat exposure (11.8 ± 0.5 vs. $13.0 \pm 0.4 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$). When the oxygen cost of exercise was expressed as a percentage of $\dot{V}O_{2 \text{ peak}}$, values were significantly greater for both UT_{High} and UT_{Low} compared with their T counterparts (26.0 ± 1.8 , 26.5 ± 1.1 , 20.4 ± 1.0 , and $22.7 \pm 1.6\%$ $\dot{V}O_{2 \text{ peak}}$ for UT_{Low} , UT_{High} , T_{Low} , and T_{High} , respectively).

SR and body mass loss. The SR for T_{High} ($0.59 \pm 0.03 \text{ kg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$) was significantly different from that for UT_{High} ($0.35 \pm 0.03 \text{ kg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$). In the UT groups, UT_{Low} ($0.49 \pm 0.02 \text{ kg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$) was significantly greater than UT_{High} . The SR for T_{Low} was $0.53 \pm 0.03 \text{ kg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$. There were also observed differences in percent body mass change. T_{High} had a significantly greater percent body mass loss compared with UT_{High} (0.63 ± 0.16 vs. $0.08 \pm 0.13\%$), because T subjects lasted longer without water in the latter stages of their trial than their UT counterparts because of the rehydration schedule. However, body mass changes were $<0.8\%$ total body mass for all groups.

RPE and RTC. As expected, RPE increased throughout the heat-stress exposure for all groups, but values were significantly lower for the T compared with the UT . Specifically, RPE was lower for T_{Low} (1.8 ± 0.5) compared with UT_{Low} (3.7 ± 0.4) at 30 min and beyond during the heat-stress exposure. Similarly, RPE for T_{High} (2.9 ± 0.6) was significantly lower than for UT_{High} (4.8 ± 1.1) after 45 min of the trial. RPE was also significantly reduced for T_{Low} (3.8 ± 0.8) compared with T_{High} (6.3 ± 1.1) after 75 min of heat-stress exposure. RTC also increased throughout the heat-stress exposure, and overall high-fit subjects (8.3 ± 0.1) displayed lower RTC than their less-fit counterparts (9.2 ± 0.1). In addition, T_{Low} (7.8 ± 0.4) displayed lower ratings than UT_{Low} (9.0 ± 0.4) after 30 min of exercise, and these significant differences continued for the remainder of the heat-stress exposure. There were no other significant differences among matched groups.

Heat storage. There were no differences among the matched groups in metabolic rate, evaporative heat

loss, radiative and convective heat gain, or respiratory heat loss. The mean $\dot{S}$, however, was significantly greater in UT_{Low} and T_{High} compared with UT_{High} (Table 5), despite the similar exercise times. Over 80% of these differences in $\dot{S}$ could be attributed to the differences in metabolic rate. As well, there was an interaction of fitness and fatness on the heat storage capacity expressed per unit of total mass. Heat storage for T_{Low} was greater than both its matched fitness (T_{High}) and fatness (UT_{Low}) counterparts, and T_{High} was greater than UT_{High} . However, there was no difference in $\dot{S}$ between the UT groups.

DISCUSSION

One approach to study the impact of different physical characteristics on thermoregulation during exercise is to examine the response of subjects with a wide range of values for characteristics such as fitness, fatness, mass, and surface area during exposure to the same environmental conditions. Such an approach has been used by Havenith et al. (22, 24, 25) to study dry and humid heat-stress exposure. Although the importance of this work cannot be understated, subjects were not exercised to exhaustion, and, as such, conclusions concerning the importance of different characteristics on heat tolerance could not be made. Another approach to study this question is to match subjects for those factors that have been shown previously to influence tolerance to a given heat-stress environment. Such an approach was used in the present investigation that was designed to further clarify the roles that aerobic fitness and body fatness play in the uncompensable heat-stress environment. Although comparisons between T_{Low} and UT_{Low} and between T_{Low} and T_{High} clearly revealed the advantage of an increased aerobic fitness and a decreased body fatness, respectively, it was equally apparent that differences in the $\dot{S}$, attributable to differences in movement efficiency, were also an important factor that could account for differences in tolerance to a given set of uncompensable heat-stress conditions.

In the present study, aerobic fitness was defined relative to lean rather than total body mass to remove the influence of body fatness on the expression of fitness. High-fat subjects had a significantly higher body mass compared with the low-fat groups. Thus the expression of $\dot{V}O_{2 \text{ peak}}$ relative to total mass was signifi-

Table 5. $\dot{M}$, $\dot{E}_{sk}$, $\dot{R} + C$, $\dot{E}_{resp} + C_{resp}$, $\dot{S}$, and S during heat-stress trial conducted at 40°C and 30% relative humidity, with subjects wearing the protective clothing ensemble for T or UT with low or high body fatness

Group	$\dot{M}$, W/kg	$\dot{E}_{sk}$, W/kg	$\dot{R} + C$, W/kg	$\dot{E}_{resp} + C_{resp}$, W/kg	$\dot{S}$, W/kg	S , kJ/kg
T_{Low}	4.73 ± 0.22	1.44 ± 0.13	0.35 ± 0.051	0.38 ± 0.011	3.27 ± 0.18	$22.20 \pm 1.17\ddagger$
T_{High}	4.78 ± 0.19	1.38 ± 0.22	0.30 ± 0.009	0.38 ± 0.008	$3.41 \pm 0.16\ddagger$	$16.96 \pm 0.75^{*\ddagger}$
UT_{Low}	4.95 ± 0.25	1.45 ± 0.20	0.34 ± 0.015	0.40 ± 0.019	$3.52 \pm 0.19\ddagger$	14.46 ± 0.71
UT_{High}	4.35 ± 0.20	1.51 ± 0.11	0.31 ± 0.019	0.36 ± 0.024	2.87 ± 0.19	12.70 ± 1.27

Values are means $\pm$ SE. $\dot{M}$, metabolic heat production; $\dot{E}_{sk}$, skin evaporation rate; $\dot{R} + C$, radiative and convective heat loss; $\dot{E}_{resp} + C_{resp}$, respiratory heat loss and convective heat gain; $\dot{S}$, rate of heat storage; S , total heat storage. Rate of external work and conductive heat gain were considered zero because subjects were walking on a level treadmill. Significant differences: $^*T_{High}$ vs. T_{Low} ; $^{\ddagger}UT_{High}$ vs. UT_{Low} ; $^{\ddagger}T_{High}$ vs. UT_{High} ; $^{\ddagger}T_{Low}$ vs. UT_{Low} , $P < 0.05$.

cantly reduced for the high-fat groups compared with their matched counterparts (see Table 2). Therefore, by defining $\dot{V}O_2$ in terms of LBM, a confounding influence of body fatness was eliminated. The inclusion of activity level as an additional grouping criterion was used because of the observation that $\dot{V}O_{2\text{ peak}}$ alone correlates only moderately with heat tolerance and the presence of training-induced adaptations to heat exposure (4, 29). Hence, classifying a sedentary subject with a naturally high $\dot{V}O_{2\text{ peak}}$ as trained was avoided.

We also attempted to control confounding states of hydration before and during the heat-stress trial. Hypohydration is associated with increased cardiovascular and thermoregulatory strain during exercise (7, 43) and can lead to a decreased tolerance to uncompensable heat stress, regardless of fitness (9, 43). Fluid replacement decreases physiological strain during exercise in the heat (6) and has also been shown to produce a decreased cardiovascular strain while exercising in protective clothing (11). In the present study, some T subjects continued to exercise at $T_{re} > 39^\circ\text{C}$ for ~ 30 min. Because fluid replacement ceased at this core temperature because of uncertainties about how much longer a subject might continue, this created a situation that, when combined with the increased SR values, produced a greater loss in body mass. However, the percentage of body mass lost due to dehydration did not exceed 0.8% for any group, thus minimizing the deleterious effects of dehydration (11). Nonetheless, differences in exercise time between T and UT groups may have been even greater had all subjects remained euhydrated throughout the heat stress.

The fit of the protective clothing ensemble is also another potential confounding variable. Air trapped between clothing layers acts as a barrier against convective and evaporative heat transfer between the environment and skin (21). Because air is an excellent insulator, clothing fit is an important factor when human heat response to uncompensable heat stress is examined (23). In the present study, subjects were fitted with operational clothing and a protective overgarment according to available sizes, and every attempt was made to avoid excessively tight- or loose-fitting layers of clothing.

Implications of aerobic fitness. By far, the greatest effect of aerobic fitness on exercise time during uncompensable heat stress is mediated through the core temperature tolerated at exhaustion. In the present study, differences were as great as 0.9°C between subjects with differing fitness levels matched for low body fatness. This finding is similar to the 0.7°C difference in $T_{re, final}$ observed by Cheung and McLellan (9). All subjects in the high-fit group reported by Cheung and McLellan attained the ethical ceiling of 39.3°C for T_{re} and also felt that they could have continued. Similarly, all subjects in T_{Low} attained the ethical ceiling of 39.5°C and felt that they could have continued. Given that their rate of increase in T_{re} during the last 15 min of heat exposure was 1.7°C/h , T_{Low} subjects could have continued to exercise a further 18 min before reaching a T_{re} of 40.0°C . In contrast, the two subjects in UT_{Low}

who terminated their trial, having reached the ethical ceiling for HR, could have continued to exercise for a further 9 min before attaining maximal HR. Thus differences in exercise time between fit and unfit subjects were most likely underestimated, and differences in the T_{re} tolerated at exhaustion between fit and unfit subjects are also most likely to be conservative estimates. Recent evidence has documented that fatigue during heat stress is associated with the attainment of a critically high core temperature, approaching 40°C for endurance-trained subjects (19, 20, 40, 41). These subjects would be quite similar to those defined as T_{Low} in the present investigation. The lower core temperature of $\sim 38.7^\circ\text{C}$ tolerated at exhaustion for the UT groups in the present study is consistent with previous work that has examined a similar subject population (9, 10) or studies that have reported findings from subjects with a wide range of fitness levels (11, 31, 33, 36, 39). Thus differences in aerobic fitness appear to account for the discrepancies in the literature describing the core temperatures that can be tolerated at exhaustion during uncompensable heat stress.

It is unclear why the core temperature that can be tolerated at exhaustion during uncompensable heat stress is considerably less for sedentary subjects. The untrained experience greater circulatory strain at any given core temperature during heat stress because of their lower blood volume and stroke volume (27), and it is tempting to suggest that these differences may account for the lower core temperature tolerated at exhaustion. Yet, in the present study, only 2 of 12 UT subjects terminated their trial because HRs reached the ethical ceiling of 95% of peak values, and final HRs were not different among the groups, averaging 85–90% of peak values. To our knowledge, there has not been a systematic comparison of the cardiovascular responses during exhaustive exercise in uncompensable heat-stress conditions between endurance-trained and untrained subjects that might explain the reason for the differing core temperatures that can be tolerated.

Sawka et al. (43) reported that there was no relationship between the core temperature tolerated at exhaustion during uncompensable heat stress and the $\dot{V}O_{2\text{ max}}$ of their heat-acclimated subjects. Similarly, in the present study, for the 10 subjects who ended their trial because of exhaustion or nausea, there was no relationship between the core temperature tolerated at exhaustion and $\dot{V}O_{2\text{ peak}}$ expressed relative to LBM or total body mass. Therefore, although endurance-trained individuals can tolerate higher core temperatures, this advantage is not directly proportional to their level of aerobic fitness. It is interesting in the present study that the perception of the physiological strain was significantly reduced for the high-fit subjects. It is possible, therefore, that the higher core temperatures tolerated by the endurance trained are acquired partially through the familiarization of regular aerobic training and exposure to higher body temperatures on a daily basis.

It is important to realize that, when protective clothing is worn that restricts evaporative heat loss, aerobic fitness exerts its impact by increasing the core temperature that can be tolerated at exhaustion rather than promoting greater evaporative heat loss and slowing the $\dot{S}$. Because the characteristics of the clothing (and the environment) determine the evaporative heat loss, it is the absolute rate of heat production that is the major determinant for the $\dot{S}$ (see Table 5). Thus absolute (expressed per unit of mass) rather than relative (expressed as $\% \dot{V}O_{2 \max}$) exercise intensities are more appropriate to normalize the heat-stress response (24, 35, 36).

Implications of body fatness. Because of its lower heat capacity compared with lean tissue such as blood, water, bone, and skeletal muscle (15), an increase in adipose tissue will reduce the overall $C_{p,b}$. Thus, for a given $\dot{S}$, the rate of change in tissue and body temperature will be dependent on the proportion and distribution of body fat. This is consistent with previous comparisons between men and women that involved wearing protective clothing in the heat (36) and comparisons between the T groups in the present investigation. T_{Low} also had a significantly greater overall increase in T_{re} from the beginning to the end of the heat-stress exposure compared with T_{High} (see Table 3). It is possible, therefore, that a reduced body fatness also increases the core temperature that can be tolerated at exhaustion, independent of the effect of aerobic fitness.

Implications of $\dot{S}$. This study was designed under the assumption that $\dot{S}$ would be similar among the groups. Previous studies have shown that the clothing layers and materials of the protective ensemble limit the evaporative heat loss to between 50 and 60 W/m² (34, 37) with the environmental conditions used in the present investigation. Because all subjects performed the same treadmill exercise, it was expected that metabolic rates would be similar for all subjects. This was not the case for UT_{High} subjects, who had a reduced oxygen cost of walking per unit of mass compared with the other groups. We cannot explain why these subjects were more efficient walkers on the treadmill. Nonetheless, this difference translated into a lower $\dot{S}$ for these subjects that countered their disadvantage of higher body fatness.

The reader should be cognizant of the fact that the findings for this study are specific for weight-bearing activity. The components of the heat balance equation and the determination of $\dot{S}$ and heat storage capacity were purposely expressed per unit of mass, because the exercise required the subject's mass to be carried. However, for weight-supported exercise, such as cycling, a larger body mass would be an advantage because heat production is independent of mass. Exercise time during weight-supported exercise in an uncompensable heat-stress environment would be influenced more by the size of the individual and the core temperature that could be tolerated at exhaustion.

In summary, this study has shown that aerobic fitness, body fatness, and $\dot{S}$ can each have a significant

impact on tolerance to low-intensity weight-bearing exercise in a hot environment while wearing protective clothing. The main benefit attributed to a high aerobic fitness was the ability to tolerate higher core temperatures at exhaustion, with this difference being as great as 0.9°C.

The authors thank D. Kerrigan-Brown and I. Smith, and R. Lammer and J. Pope for technical assistance. The time and effort of the subjects in this investigation are greatly appreciated.

REFERENCES

- Amos D and Hansen R. The physiological strain induced by a new low burden chemical protective ensemble. *Aviat Space Environ Med* 68: 126-131, 1997.
- Aoyagi Y, McLellan TM, and Shephard RJ. Effects of training and acclimation on heat tolerance in exercising men wearing protective clothing. *Eur J Appl Physiol* 65: 234-245, 1994.
- Aoyagi Y, McLellan TM, and Shephard RJ. Effects of 6 versus 12 days of heat acclimation on heat tolerance in lightly exercising men wearing protective clothing. *Eur J Appl Physiol* 71: 187-196, 1995.
- Avellini BA, Shapiro Y, Fortney SM, Wenger CB, and Pandolf KB. Effects of heat tolerance of physical training in water and on land. *J Appl Physiol* 53: 1291-1298, 1982.
- Borg GAV. Psychophysical bases of perceived exertion. *Med Sci Sports Exerc* 14: 377-381, 1972.
- Candas V, Libert JP, Brandenberger G, Sagot JC, Amoros C, and Kahn JM. Hydration during exercise: effects on thermal and cardiovascular adjustments. *Eur J Appl Physiol* 55: 113-122, 1986.
- Candas V, Libert JP, Brandenberger G, Sagot JC, and Kahn JM. Thermal and circulatory responses during prolonged exercise at different levels of hydration. *J Physiol (Paris)* 83: 11-18, 1988.
- Carter BJ and Cammermeyer M. Emergence of real casualties during simulated chemical warfare training under high heat conditions. *Mil Med* 150: 657-665, 1985.
- Cheung SS and McLellan TM. Heat acclimation, aerobic fitness, and hydration effects on tolerance during uncompensable heat stress. *J Appl Physiol* 84: 1731-1739, 1998.
- Cheung SS and McLellan TM. Influence of short-term aerobic training and hydration status on tolerance to uncompensable heat stress. *Eur J Appl Physiol* 78: 50-58, 1998.
- Cheung SS and McLellan TM. Influence of hydration status and fluid replacement on heat tolerance while wearing NBC protective clothing. *Eur J Appl Physiol* 77: 139-148, 1998.
- Cheung SS, McLellan TM, and Tengalis SA. The thermophysiology of uncompensable heat stress. Physiological manipulations and individual characteristics. *Sports Med* 29: 329-359, 2000.
- Dubois D and Dubois EF. A formula to estimate the approximate surface area if height and weight be known. *Arch Intern Med* 17: 863-871, 1916.
- Gagge AP, Stolwijk JAJ, and Hardy JD. Comfort and thermal sensations and associated physiological responses at various ambient temperatures. *Environ Res* 1: 1-20, 1967.
- Gephart FC and Dubois EF. Clinical calorimetry, fourth paper. The determination of the basal metabolism of normal men and the effect of food. *Arch Intern Med* 15: 833-845, 1915.
- Givoni B and Goldman RF. Predicting rectal temperature response to work, environment, and clothing. *J Appl Physiol* 32: 812-822, 1972.
- Goldman RF. Tolerance time for work in the heat when wearing CBR protective clothing. *Mil Med* 128: 776-786, 1963.
- Gonzalez RR, Levell CA, Strooschein LA, Gonzalez JA, and Pandolf KB. Copper Manikin and Heat Strain Model Evaluations of Chemical Protective Ensembles for the Technical Cooperation Program (TTCP). Natick, MA: US Army Research Institute of Environmental Medicine, 1993. (Tech. Rep 94-4)
- Gonzalez-Alonso J, Calbet JAL, and Nielsen B. Metabolic and thermodynamic responses to dehydration-induced reduc-

- tions in muscle blood flow in exercising humans. *J Physiol (Lond)* 520: 577-589, 1999.
20. Gonzalez-Alonso J, Teller C, Andersen SL, Jensen FB, Hyldig T, and Nielsen B. Influence of body temperature on the development of fatigue during prolonged exercise in the heat. *J Appl Physiol* 86: 1032-1039, 1999.
 21. Havenith G. Heat balance when wearing protective clothing. *Ann Occup Hyg* 43: 289-296, 1999.
 22. Havenith G, Coenen JML, Kistemaker L, and Kenny WL. Relevance of individual characteristics for human heat stress response is dependent on exercise intensity and climate type. *Eur J Appl Physiol* 77: 231-241, 1998.
 23. Havenith G, Heus R, and Lotens WA. Resultant clothing insulation: a function of body movement, posture, wind, clothing fit and ensemble thickness. *Ergonomics* 33: 67-84, 1990.
 24. Havenith G, Luttikholt VGM, and Vrijkotte TGM. The relative influence of body characteristics on humid heat stress response. *Eur J Appl Physiol* 70: 270-279, 1995.
 25. Havenith G and van Middendorp H. The relative influence of physical fitness, acclimatization state, anthropometric measures and gender on individual reactions to heat stress. *Eur J Appl Physiol* 61: 419-427, 1990.
 26. Henane R, Bittel J, Viret R, and Morino S. Thermal strain resulting from protective clothing of an armored vehicle crew in warm conditions. *Aviat Space Environ Med* 50: 599-603, 1979.
 27. Hopper MK, Coggan AC, and Coyle EF. Exercise stroke volume relative to plasma-volume expansion. *J Appl Physiol* 64: 404-408, 1988.
 28. Kakitsuba N and Mekjavic IB. Determining the rate of body heat storage by incorporating body composition. *Aviat Space Environ Med* 58: 301-307, 1987.
 29. Kielblock AJ. Heat acclimatization with special reference to heat tolerance. In: *Man in Stressful Environments*, edited by Shiraki K and Yousef MF. Springfield, IL: Thomas, 1987, p. 145-152.
 30. Kraning KK and Gonzalez RR. Physiological consequences of intermittent exercise during compensable and uncompensable heat stress. *J Appl Physiol* 71: 2138-2145, 1991.
 31. Latzka WA, Sawka MN, Montain SJ, Skrinar GS, Fielding RA, Matott RP, and Pandolf KB. Hyperhydration: tolerance and cardiovascular effects during uncompensable exercise-heat stress. *J Appl Physiol* 84: 1858-1864, 1998.
 32. McLellan TM. Work performance at 40°C with Canadian Forces biological and chemical protective clothing. *Aviat Space Environ Med* 64: 1094-1100, 1993.
 33. McLellan TM. Sex-related differences in thermoregulatory responses while wearing protective clothing. *Eur J Appl Physiol* 78: 28-37, 1998.
 34. McLellan TM, Gannon GA, Zamecnik J, Gil V, and Brown GM. Low doses of melatonin and diurnal effects on thermoregulation and tolerance to uncompensable heat stress. *J Appl Physiol* 87: 308-316, 1999.
 35. McLellan TM, Jacobs I, and Bain JB. Influence of temperature and metabolic rate on work performance with Canadian forces NBC clothing. *Aviat Space Environ Med* 64: 587-594, 1993.
 36. McLellan TM, Pope JI, Cain JB, and Cheung SS. Effects of metabolic rate and ambient vapour pressure on heat strain in protective clothing. *Eur J Appl Physiol* 74: 618-627, 1996.
 37. McLellan TM, Smith IF, Gannon GA, and Zamecnik J. Melatonin has no effect on tolerance to uncompensable heat stress in man. *Eur J Appl Physiol* 83: 336-343, 2000.
 38. Mitchell JW, Nadel ER, and Stolwijk JAJ. Respiratory weight losses during exercise. *J Appl Physiol* 32: 474-476, 1972.
 39. Montain SJ, Sawka MN, Cadarette BS, Quigley MD, and McKay JM. Physiological tolerance to uncompensable heat stress: effects of exercise intensity, protective clothing, and climate. *J Appl Physiol* 77: 218-222, 1994.
 40. Nielsen B, Hales JRS, Strange S, Christensen NJ, Warberg J, and Saltin B. Human circulatory and thermoregulatory adaptations with heat acclimation and exercise in a hot, dry environment. *J Physiol (Lond)* 460: 467-485, 1993.
 41. Nielsen B, Strange S, Christensen NJ, Warberg J, and Saltin B. Acute and adaptive responses in humans to exercise in a warm, humid environment. *Pflugers Arch* 434: 49-56, 1997.
 42. Rowell LB. *Human Circulation, Regulation During Physical Stress*. New York: Oxford University Press, 1986.
 43. Sawka MN, Young AJ, Latzka WA, Neuffer PD, Quigley MD, and Pandolf KB. Human tolerance to heat: strain during exercise. influence of hydration. *J Appl Physiol* 73: 368-375, 1992.
 44. Siri WE. The gross composition of the body. In: *Advances in Biological and Medical Physics*. New York: Academic, 1956, vol. 4, p. 239-280.
 45. Snellen JW. Mean body temperature and the control of thermal sweating. *Acta Physiol Pharmacol Neerl* 14: 99-174, 1966.
 46. Tenaglia SA, McLellan TM, and Klentrou PP. Influence of menstrual cycle and oral contraceptives on tolerance to uncompensable heat stress. *Eur J Appl Physiol* 80: 76-83, 1999.
 47. Vallerand AL, Limmer R, and Schmiegner IF. Computer acquisition and analysis of skin temperature and heat flow data from heat flux transducers. *Comput Methods Programs Biomed* 30: 279-282, 1989.

